HEP Science Connections Study: Who, What, Why & How?

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- Jim Siegrist's charge to us: survey possible intellectual connections between HEP and other sciences beyond the current HEP purview. More specifically:
  - How might such connections be exploited to advance science as a whole, particle physics itself, and/or the missions of other DoE offices?
  - Can we identify novel and exciting "grand challenges" that can be pursued at the interface of particle physics and other basic sciences?
- We took this on because we think it is right (and timely) to develop and publicize the broader benefits of HEP to science and to society as a whole.
- Our method was to interview "experts" in a range of fields, chosen for their track record in addressing broader questions of science management.
  - Disclaimer: This is really a study for a study, not the finished product. Also, we address the problem from a theoretical physics viewpoint.

We asked people from many disciplines for their views

- Astrophysics (Roger Blandford, Jeremy Goodman)
- Nuclear Physics (K. Rajagopal, H. Robertson, M Ramsey-Musolf)
- Fusion Plasma (Stewart Prager, Ronald Davidson)
- Atomic and Molecular Physics (David deMille, Savas Dimopoulos)
- Condensed Matter (Subir Sachdev, Paul Steinhardt, Ashvin Vishwanath)
- Quantum Information Science (Chetan Nayak, John Preskill)
- Mathematics (Miriam Cvetic, Mike Douglas, S-T Yau)
- Climate Science (Bill Collins, Andy Majda, Inez Fung)
- Biology (Herbert Levine, Larry Abbott, Terry Sejnowski)
- Econophysics (George Papanicolao, David Shaw)
- NB: We are grateful to our consultants for their time and wisdom. They are not responsible for sins of omission and/or commission on our part!

Responses were quite varied, as sample quotes will show:

- The largest unexplored synergy seems to lie in using the HEP human, organizational and physical infrastructure to advance the most exciting science around. There are skills ... present in the particle physics community that are in short supply and needed in other, rapidly growing fields. (Astro)

- The most compelling opportunity ... is in measurements of electric dipole moments and closely related phenomena ... university-national lab collaborative efforts, involving a handful of PIs ... could help to advance this field much more quickly than has been the norm over the past 20 years. (AMO)

- It is not HEP theoretical techniques that are the valuable resource for cross-fertilization; it is the HEP theoretical talent. I would like to see DoE HEP seed work that encourages that substantial pool of theoretical talent to take chances to ... make big breakthroughs ... in less charted areas within CM (Cond Mat)

- Particle physics has always attracted exceptionally smart students, and it provides an outstanding training in clear thinking ... The impact of this can be seen in ... the life sciences, where former physicists, and particle physicists in particular, are often leading figures. (Neuro)

Responses were quite varied, as sample quotes will show:

- Neuroscience is poised to join genomics, astronomy and physics in developing big science projects. High Energy Physics could have a major impact on the way that signals are sensed and data collected .. (and) make a difference in accelerating progress in brain theory. (Neuro)
- There are many compelling synergies between research in elementary particle physics and research in plasma physics ... Can advances be made by sharing mathematical or computational techniques among these disciplines? A possible area of collaboration is Sub-Grid Scale (SGS) models. (Plasma)
- A variety of concepts originating in particle physics have filtered into the theory of quantum error correction ... (and) quantum computers may provide an indispensable tool for probing the properties of non-perturbative string theory. (Quantum Info/Computing)
- It is clear that the challenges posed by contemporary research in finance are profound and at a level (of complexity) comparable to high-level research in theoretical physics and mathematics. The methods needed in this research can also benefit from comparable research done in physics (Econo)
- There are ... opportunities for knowledge transfer from the physics to the climate community on how best to construct multiphysics models and to use them to test falsifiable hypotheses ... (do) uncertainty quantification in high-dimensional parameter spaces ..(and) significance testing using extrapolation from a limited number of numerical calculations

There are some common threads in this diversity

- All respondents were enthusiastic about the idea that HEP might "reach out" to fields beyond its current explicit mission. They were unanimous on this point.
- The "near by" fields (AMO, Nuclear, Astro) generally wanted HEP to expand its mission to include a broader range of science that DoE people/institutions are equipped to do. Some well-defined cross-discipline project proposals emerged.
- Past discoveries in particle physics have transformed "near by" disciplines, esp. nuclear physics and cosmology. CMP and quantum info science may have a similar evolution. Ideas on on how to facilitate this process are taking shape.
- The "near neighbor" (Climate, Plasma) and "far-out" (Bio, Econo) disciplines see a growing need fo intellectual "capital" similar to that built up by HEP over time:
  - In part this has to do the growing importance of big science/big data: exporting HEP skills in this domain could have a broad scientific impact.
  - Also, the intellectual problems of these fields are increasing in mathematical sophistication ... and are approaching the level we are accustomed to in HEP
  - More than anything, these fields would like to bring our human capital to bear on their problems (by raiding, or borrowing, HEP people).
  - But ideas on how to proceed in practice, and how to set priorities, are vague
- Virtually all respondents felt that DoE HEP should be more supportive of exploratory, outside-the-stovepipe, work (especially in theory...)

HEP: interface with "close by" subfields

This covers areas where either the underlying structure is common (quantum mechanics, quantum field theory,...) or there is a history of interaction with the cognate subfield, e.g. in measuring "fundamental" parameters.

Included here would be disciplines like AMO, nuclear physics, condensed matter physics, mathematics, quantum information,...

Are there substantially new frontiers here to be exploited? Here are some ideas we encountered.

In AMO:

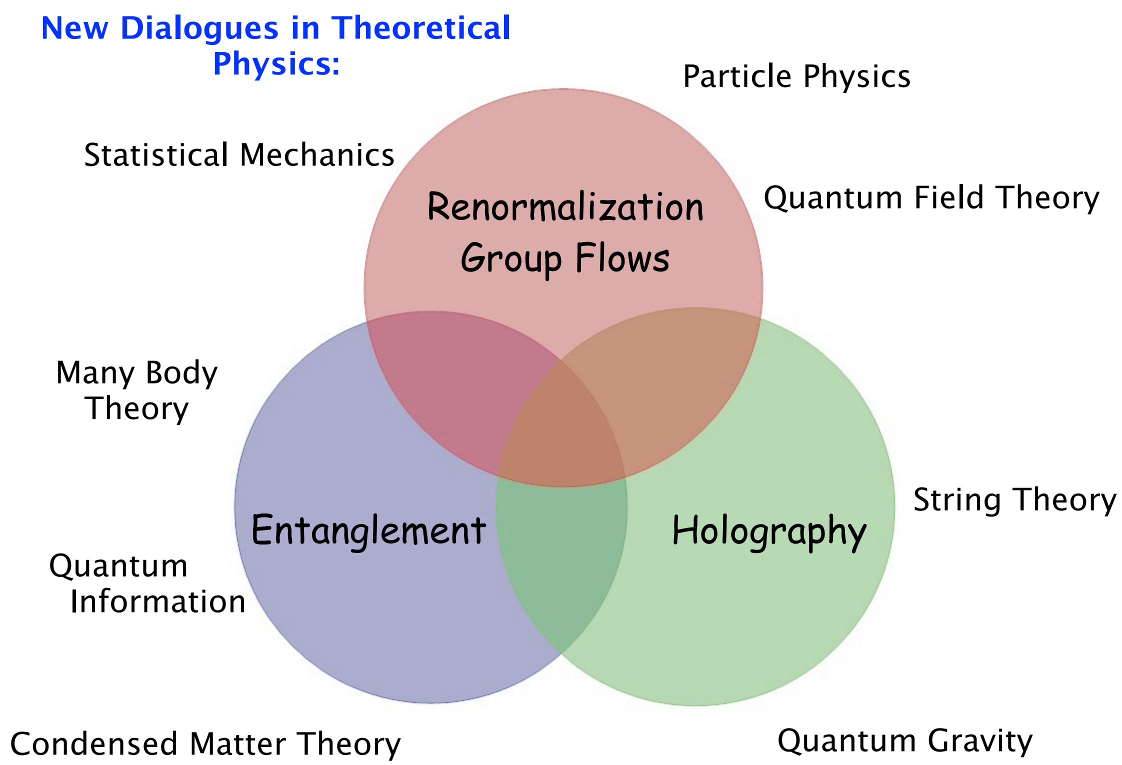
* Long history of healthy interaction measuring EDMs (though neutron EDM is covered by nuclear physics). One of the few reliable windows on new physics (CP violation), independent of high energy accelerators.

"I strongly suspect some type of multi-university or university-national lab collaborative efforts, involving a handful of PIs..., could advance this field much more quickly." (D. DeMille, Yale)

* New modes of detecting axions or gravity waves are now being proposed, using precision magnetometry and atom interferometry...

"These provide new tools...for probing fundamental laws. They are characterized by high precision or high coherence, instead of high energy..." (S. Dimopoulos, Stanford)

There is a large overlap of interests between portions of HEP, CMP, AMO, nuclear, and quantum information communities:



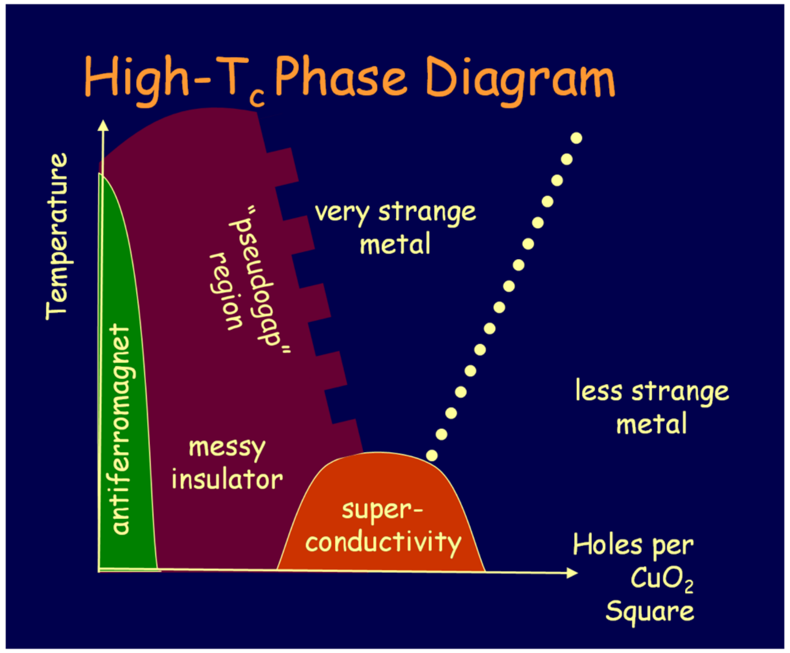
Renaissance using modern tools of QFT, together with entanglement, to provide new windows on issues ranging from novel topological states of condensed matter to emergence of space-time

Key issues to address: experimental "quantum simulation" and theoretical understanding of strongly correlated systems (Hubbard model? QGP? Non-Abelian gauge fields?). Interests overlap between HEP and all of these neighboring communities. Great chance to develop a dialogue and exchange tools, ideas, and unsolved problems!

With Condensed Matter Physics in particular:

Common language of quantum field theory and RG unifies (significant parts of) the two disciplines.

Important (conceptually, technologically?) new states of matter still evade proper description in this language:

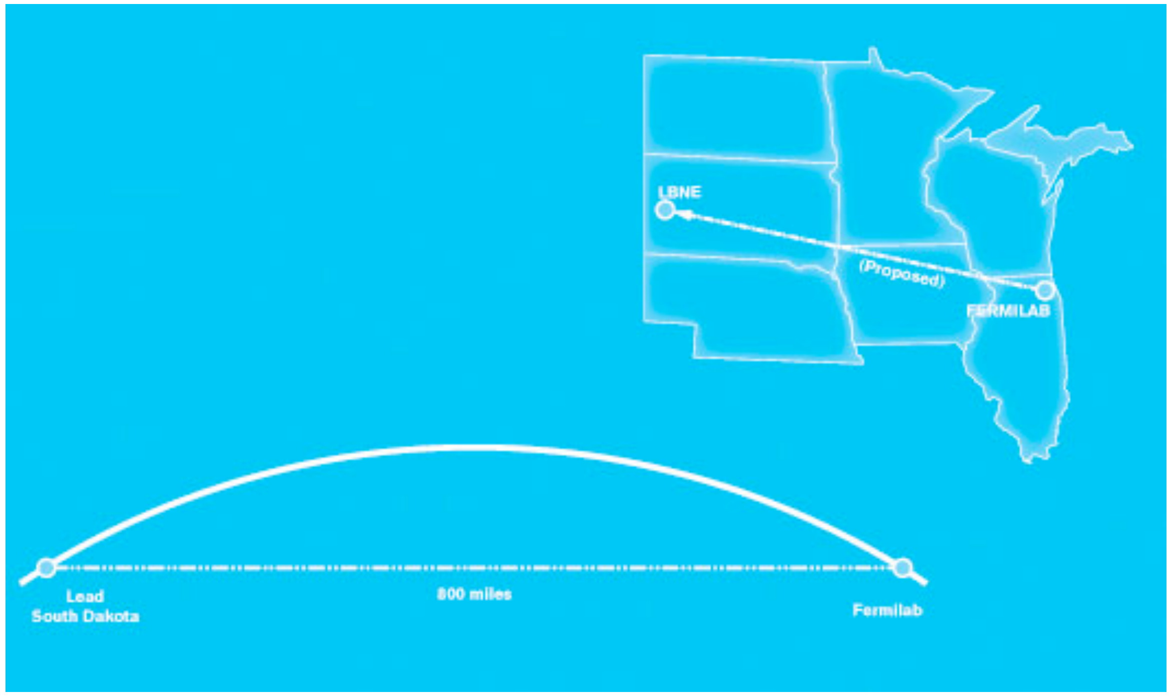


"Many important correlated electron materials display strange metal regimes where a description based on quasiparticles breaks down...much insight has been gained by [HET techniques]."
(S Sachdev, Harvard)

"...in recent times, we have been confronted with strongly coupled problems...where non-perturbative techniques are sorely required."
(A Vishwanath, UC Berkeley)

"It is not the HEP theoretical techniques that are the valuable resource for cross-fertilization; it is the HEP theoretical talent...I would suggest making a new pipe...designed to seed/encourage HEP physicists to contribute to other areas."
(P Steinhardt, Princeton)

With Nuclear Physics there are some very specific overlaps of possible import in near future. For instance:



* For LBNE and other neutrino oscillation studies, important to get good neutrino/nucleus cross sections.

* New ideas using storage rings to do better EDM experiments on isolated nucleons

* Obvious and continuing overlaps of interest in searches for WIMP dark matter, neutrinoless double beta decay experiments, and so forth.

The take home message in the "close-by" fields is that there are several new and rapidly developing interfaces between HEP and cognate fields. These could be nurtured in a few ways:

"... much exciting research is happening at the interface between areas, and this will only increase in the future...it can easily be achieved by promoting and rewarding research that crosses traditional DOE boundaries." (S. Sachdev, Harvard)

"Support for young people...to have the time to learn about both fields and find their own style of research at the interface..." (C. Nayak, UCSB / Station Q)

In addition to mechanisms to relax stove-piping, it could be fruitful to have workshops involving leaders from all relevant subfields, to identify key challenges that the communities can meet together.

HEP interface with "near neighbor" disciplines

- In this category we place astrophysics, plasma physics, and climate science: fields with strong links to fundamental physics (and DoE Office of Science).
- Astrophysics includes the HEP Cosmic Frontier. Important "applied" astro-physics goals are "shovel ready" for inclusion in the HEP program. Examples:
  - Ground-based CMB observations. (Possible probe of inflationary physics at enormously high energies).
  - Support for observations other than optical at the Cosmic Frontier as a source of knowledge about Dark Matter/Energy.
  - More generally, "There are skills ... abundantly present in the particle physics community that are in short supply and needed in other, rapidly growing fields." (R. Blandford, SLAC/Stanford)

HEP interface with “near neighbor” disciplines

- Plasma physics and climate science consultants pointed out the existence of deep theory problems in their fields: turbulence, multi-scale physics simulation, etc.
  - They believe that, in addition to brute force computation, conceptual advances will be needed to reach the ambitious goals of these fields (the prediction, with quantifiable uncertainty, of future climate statistics as an example of such a goal).
  - While there is no direct map of HEP resources onto these problems, there are growing, very promising, intellectual overlaps between HEP and these disciplines (field theories of turbulence, lattice simulation of multi-scale QCD physics, AdS/CFT insights into fluid dynamics, ...).
  - Using the example of the role played by “fundamental” theoretical physicists (in the 50s-60s) in developing turbulence theory, they argue that re-engaging HEP theorists with the problems of these fields would be beneficial to both sides, and could have major impact.

HEP interface with "far out" disciplines

- Here we include cell biology, neurobiology, "social" science: fields with exploding data and science opportunities, but with historically weak links to physics.
- Consultants agreed that progress in these fields requires the invention of mathematical frameworks to comprehend the large volumes of data that are accumulating. This is a slow-moving process, with lots of roadblocks.
- To speed things up, they would like to recruit HEP people more systematically. They see HEP as a large reservoir of people with the training and mindset needed for this task (historical examples abound: Delbruck,Hopfield, ...).
  - They observe that opening such a career path, might benefit HEP recruitment as well!
- In addition, these fields are beginning to see the need for "big science" projects The Brain Activity Map Project is a striking current example.
  - This project will need theoretical innovation, instrument development, and big data management, possibly approaching the scale of complexity of big HEP projects.
  - DoE/HEP has unique experience (and success) in this domain. Mobilizing some HEP resources to help a national initiative like Brain Activity Map succeed would seem like good public relations (and exciting science). How, concretely, to proceed remains unclear.
- There is an important subtext here: these fields are growing like mad in scientific weight and societal impact. "Fundamental" physical science (i.e. HEP) has a lot to gain by establishing connections with them (and a lot to lose by not doing so).

Take-away messages and possible responses

- We conclude that, if it chose to do so, HEP could have a beneficial impact on many sciences beyond its current mission.
- We can identify several levels of initiative, departing in varying degrees from current practice, that could have this effect:
  - Expand support for non-accelerator approaches to fundamental issues, as in multi-lab AMO attacks on EDMs, axions or gravity waves.
  - Expand scope of DoE Cosmic Frontier to include frontiers of pure astrophysics: make maximal use of DoE expertise in related areas.
  - Take the lead in the development of quantum simulation, seen as a solution to the strong interaction problem in QCD, nuclear physics, and condensed matter.
  - Set up a framework for long-term engagement of HEP physicists with the deep problems of other DoE offices (condensed matter physics, climate, plasma, ...).
  - Foster engagement of HEP people with cell and neuro biology by methods TBD. NCI "Physics of Cancer" as possible template? Postdoctoral programs?
  - Explore how DoE "big science" experience (and other resources) could play a key role in the "Brain Activity Map" initiative.
- This list is inspired by the responses to our survey, and is very preliminary. It is at best only suggestive of what could be done.

Take-away messages and possible responses

- Many of these initiatives would require policy changes, and we have not worried about how they might be approved and implemented. This is beyond our pay grade, but here are some observations about process:
  - We organized our thinking around disciplines at three levels of remove from HEP, with clarity about what "outreach" might mean becoming more vague with distance. It would be useful to have three separate community exercises to verify that enthusiasm for HEP outreach is indeed broadly shared.
  - Many initiatives involve "partner" organizations that would benefit in some fashion (some of them within DoE itself). Clearly, an early step in the process would be to verify that the mutual interest we have identified is shared at the managerial level.
  - Some initiatives require that two separate communities of researchers discover a common interest in a problem, which they then pursue cooperatively. The former could be facilitated by holding preparatory workshops (easy) and the latter by providing some funding for actual collaborative work (a bit harder).
  - We were struck by the strong interest in facilitating the "migration" of HEP talent, esp. early career researchers, to biology. How to do this is not obvious. Perhaps some small-scale experiments could help in figuring out what to do here.
- We close by observing that this exercise has led us to conclude that "outreach" efforts from HEP to other sciences would be good for science as a whole, and a good investment in the future of HEP itself.